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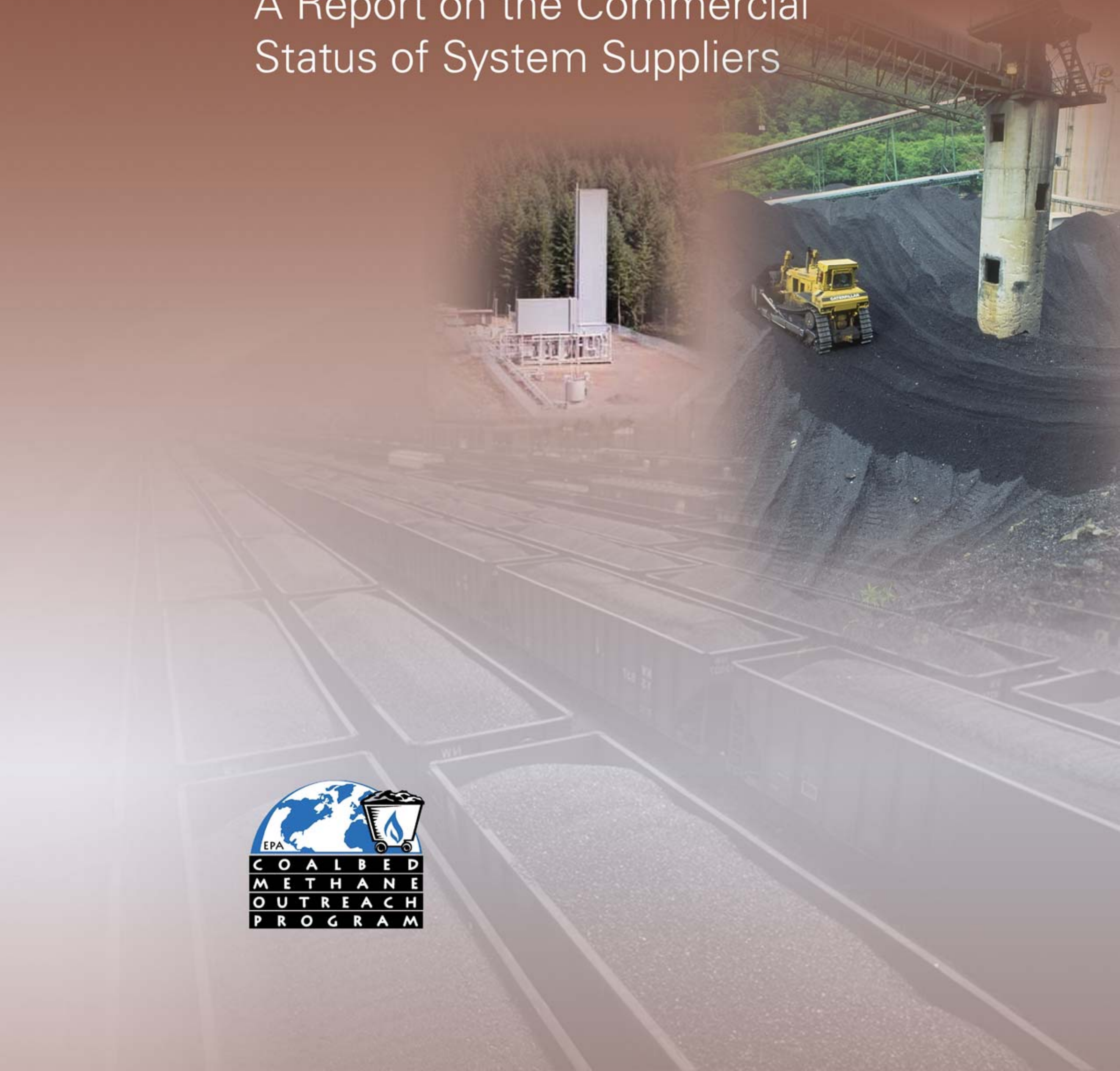
Upgrading Drained Coal Mine Methane to Pipeline Quality:
A Report on the Commercial Status of System Suppliers



EPA COALBED METHANE OUTREACH PROGRAM

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Cover Photos: Left, BCCK Nitech field installation (courtesy of BCCK Engineering, Inc.); remainder, stock coal mine images

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Preface

In 1997, the U.S. Environmental Protection Agency (USEPA) published a report titled *Technical and Economic Assessment of Potential to Upgrade Gob Gas to Pipeline Quality*. At the time, only one commercial upgrade facility was being established. During the ensuing years, three additional gas processing system suppliers have made significant progress in bringing upgrade facilities on line. This paper serves to update the 1997 report to provide information about coal mine methane upgrade system options that currently are at or near commercial readiness.

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Abbreviations and Units

AMM	Abandoned mine methane
CBM	Coal bed methane
CMM	Coal mine methane
NRU	Nitrogen rejection unit
PSA	Pressure swing adsorption
N_2	Nitrogen
O_2	Oxygen
CO_2	Carbon dioxide
H_2O	Water vapor
H_2S	Hydrogen sulfide
Btu/scf	British thermal unit per standard cubic foot
Mmscfd	Million standard cubic feet per day
ppm	Parts per million
psig	Pound per square inch, gauge
scfd	Standard cubic feet per day

1. Introduction

In today's scenario of growing energy demands worldwide and rising natural gas prices, any methane emitted into the atmosphere is an untapped resource of energy and potentially a lost opportunity for additional revenue. In 2005, 9.7 percent of the total U.S. anthropogenic emissions of methane were attributed to coal production. In recent years, many gassy coal mines have seized the opportunity to recover coal mine methane (CMM) and supply it to natural gas pipeline systems. With natural gas prices in the U.S. exceeding $7.00 per million Btu,[1] CMM pipeline sales brought in an annual revenue topping $97 million in 2005. However, significant opportunity still exists for tapping into this resource as 22 percent of the drained CMM remains unutilized as of 2005,[2] primarily because its quality does not meet the requirements of natural gas pipeline systems.

Recent advances in technologies now offer off-the-shelf options in the U.S. that can upgrade the drained CMM to pipeline quality. These gas upgrading technologies are not only opening up the market to lower-quality methane resources but are also providing significant means for reducing emissions, since methane is over 20 times a more potent greenhouse gas than carbon dioxide.

This report reviews current gas upgrading technologies available in the market for removal of typical CMM contaminants (section 3), provides examples of their successful commercial implementation (section 4), and compiles a list of vendors specific to nitrogen rejection systems (section 5), since nitrogen poses the biggest challenge to upgrading CMM.

2. Background

Using Drained CMM for Natural Gas Pipeline Sales

In general, about half of the domestic CMM emissions come from ventilation fans used to keep methane levels at underground mines within the safe range. However, many particularly gassy coal mines need to supplement their ventilation systems by drilling and operating wells to drain methane from the coal seam either before or during mining. The drained CMM typically finds end-use in the U.S. in natural gas pipeline injection.

A project manager must consider several factors for pipeline injection, including the distance and terrain to the nearest pipeline and its available capacity, the volume of methane expected to be available over the lifetime of the drainage and injection project and most importantly, the quality of the drained methane. The methane injected into the

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[1] November 2007 Henry Hub prices from http://tonto.eia.doe.gov/oog/info/ngw/ngupdate.asp. The Henry Hub, physically located at Sabine's Henry Gas Processing Plant in Louisiana, connects nine interstate and four intrastate pipelines, comprising about 49% of total US wellhead production. The Henry Hub represents the largest centralized location for natural gas spot trading in the U.S. (Philip Budzik, Energy Information Administration, *U.S. Natural Gas Markets: Relationship between Henry Hub Spot Prices and U.S. Wellhead Prices*, available at http://www.eia.doe.gov/oiaf/analysispaper/henryhub).

[2] EPA Coalbed Methane Outreach Program Accomplishments http://www.epa.gov/cmop/accomplishments.html#reducing

natural gas transmission or distribution system must meet stringent pipeline quality specifications as suggested in Table 1.

Table 1. Typical Natural Gas Pipeline Specifications[3]

Oxygen	<0.2%
Nitrogen	3% maximum
Carbon Dioxide	2% maximum
Heat Value	>967 Btu/scf minimum
Water Vapor	7 lbs/mmscf
Sales Gas Pressure	800 psig (range ~200 – 1,500 psig)

Methane drained before mining may often be of high enough quality to meet the natural gas pipeline specifications stated in Table 1 with little or no processing, generating a ready stream for substantial revenue for mine owners. However, the gas drained during mining from gob wells[4] does not typically meet natural gas pipeline specifications outright because it is more susceptible to nitrogen, oxygen, carbon dioxide, and water contamination. The same is often also true for abandoned mine methane (AMM), gas that is liberated from closed coal mines through fissures, vents, and boreholes. The methane concentration in gob gas and AMM varies widely with site-specific conditions but typically falls between 30 and 80 percent.

Gas Upgrading Options[5]

Currently, gob gas containing 50 percent methane is considered to be the low end of the range for economically viable gas upgrading. Gas containing over 90 percent methane requires relatively little cleanup for pipeline sales. Therefore, gob gas and AMM within the range of 50 to 90 percent are good candidates for upgrade.

There are four primary options to upgrade gas to pipeline quality:

1. Invest in techniques designed to improve recovery so that the gas maintains the highest possible quality. Such techniques include well and borehole design optimization and continuous monitoring systems.

2. Blend lower-quality CMM with higher-quality CMM, possibly in combination with an upgrading system. If access to high-grade blending gas is available, a less costly upgrade facility can be employed in conjunction with blending the drained CMM with higher-quality gas to bring up the CMM's quality to pipeline specifications.

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[3] Gas pressure values are from *The Transportation of Natural Gas*, available at http://www.naturalgas.org/naturalgas/transport.asp, and personal experience. Other values are from *Interstate Natural Gas – Quality Specifications & Interchangeability*, Center for Energy Economics, Bureau of Economic Geology, University of Texas at Austin, December 2004, available at http://www.beg.utexas.edu/energyecon/lng/documents/CEE_Interstate_Natural_Gas_Quality_Specifications_and_Interchangeability.pdf.

[4] Gob (or goaf) refers to the rubble zone which results when longwall mining advances and the mine roof collapses into the mined-out void. Although the primary coal seam is gone, considerable amounts of methane may continue to be released into the gob area from fractured adjacent rock strata and other, non-mined coal seams, and that methane can be extracted through wells drilled to contact the gob zone.

[5] Adapted from *Technical and Economic Assessment of Potential to Upgrade Gob Gas to Pipeline Quality*, U.S. Environmental Protection Agency, December 1997.

3. Increase the energy content of the drained gas by spiking it with higher hydrocarbon gases such as propane. This option is usually available only if the receiving pipeline is willing to accept spiked gas.

4. Install an upgrading system or enrichment plant that removes one or more of the four most prevalent contaminants.

While blending or spiking the drained CMM may help dilute the concentration of contaminants in methane, it is often necessary to employ more aggressive technologies to remove the contaminants to bring up the methane quality to pipeline specifications.

3. Gas Upgrading Technologies

Currently, several technologies are commercially available for removing the major CMM contaminants (i.e., nitrogen, oxygen, carbon dioxide, and water vapor), while some others have reached field demonstration stage of development.

Nitrogen Rejection Technologies

Nitrogen is usually the most technically difficult contaminant to remove from CMM, as well as the most expensive. Currently there are five types of available nitrogen rejection unit (NRU) technologies:

- Cryogenic Technology
- Pressure Swing Adsorption
- Solvent Absorption
- Molecular Gate
- Membrane

Cryogenic Technology: The cryogenic process uses a series of heat exchangers to liquefy the high-pressure feed gas stream. The mixture is then flashed and a nitrogen-rich stream vents from a distillation separator, leaving the methane-rich stream. Designers locate the deoxygenation system at the plant inlet to avoid the danger of explosion within the plant. Cryogenic plants have the highest methane recovery rate (about 98 percent) of any of the technologies and have become standard practice for large-scale projects where they achieve economies-of-scale; however, they tend to be less cost-effective at capacities below 5 Mmscfd which are more typical of CMM drainage projects.

Pressure Swing Adsorption (PSA): Gases when under pressure tend to get adsorbed on solid surfaces; while more gas is adsorbed with increase in pressure, reducing the pressure releases or desorbs the gas. PSA utilizes the property of varying affinities of gases for a given solid surface to separate a mixture of gases. In case of CMM, nitrogen is removed from low-quality gas by passing the gas mixture under pressure through a vessel containing an adsorbent bed that preferentially adsorbs nitrogen, leaving the gas coming out of the vessel to be rich in methane. When the adsorbent bed is saturated, the pressure is reduced to release the adsorbed nitrogen, preparing the bed for another cycle.

Usually very porous materials are selected as adsorbents for PSA systems because they provide surface areas large enough to adsorb significant amount of gas even though the adsorbed layer may be one or only a few molecules thick. Adsorbents typically used are activated carbon, silica gel, alumina, and zeolite.

Some specialty adsorbents like zeolites and carbon molecular sieves selectively adsorb gases based on the size of their molecules; only those gases are allowed into the adsorbent structure that have molecules smaller than the pore size of the absorbents. In most PSA NRU systems, wide-pore carbon molecular sieves selectively adsorb nitrogen and methane at different rates in an equilibrium condition. The use of zeolites as adsorbent for CMM has so far been tested only on bench scale.

PSA recovers up to 95 percent of available methane and can operate on a continuous basis with minimal onsite attention. PSA systems have excellent turndown capability, so they are able to operate effectively with gas flowing at a fraction of rated capacity.

Solvent Absorption: Sometimes referred to as Selective Absorption, this process uses specific solvents that have different absorption capacities with respect to different gases. In CMM applications, a solvent selectively absorbs methane while rejecting a nitrogen-rich stream in a refrigerated environment. The petroleum industry commonly uses selective absorption to enrich gas streams.

Molecular Gate: This process removes nitrogen and other contaminants from the methane, whereas other processes remove the methane from the nitrogen. The process uses a new type of molecular sieve that has the unique ability to adjust pore size openings within an accuracy of 0.1 angstrom. For CMM, the sieve pore size is set smaller than the molecular diameter of methane and above the molecular diameters of nitrogen, oxygen, carbon dioxide, and water, as indicated in Figure 1. This permits the nitrogen and other contaminants to enter the pores and be adsorbed while excluding the methane, which passes through the fixed bed of adsorbent at essentially the same pressure as the feed.

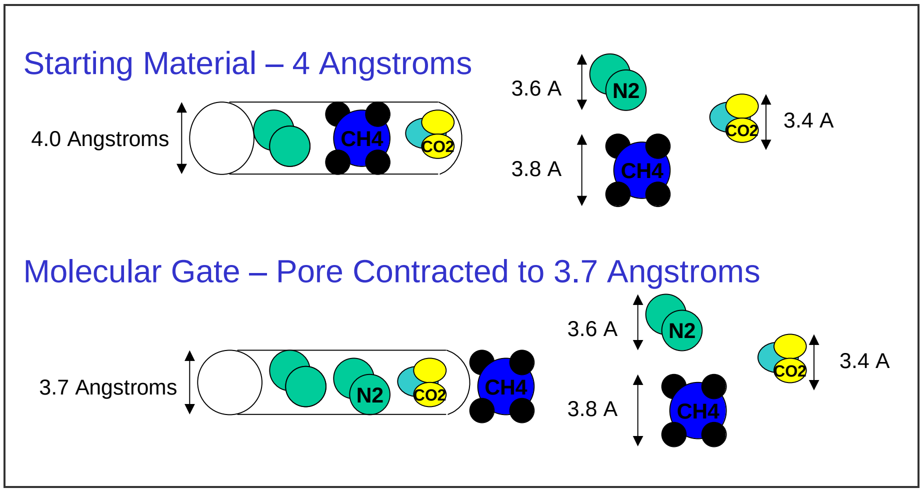

Figure 1. Molecular Gate NRU Technology (courtesy of Engelhard)

The molecular gate process employs a PSA operation by "swinging" the adsorbent bed pressure from a high-pressure feed step that adsorbs the contaminants to a low-pressure regeneration step to remove the previously adsorbed contaminants.

Membrane: This process uses membranes to selectively pass methane, ethane, and higher hydrocarbons while retaining nitrogen. A simple one-stage membrane unit is appropriate for feed gas containing about 6 to 8 percent nitrogen. However, more commonly, nitrogen concentrations are higher and require a two-step or two-stage membrane system.

Oxygen, Carbon Dioxide, and Water Vapor Removal Technologies

Systems to remove oxygen, carbon dioxide, or water vapor can stand alone, but typically, an integrated enrichment facility is installed to remove all four contaminants with a series of connected processes at one location. When a facility consists of components from more than one vendor, a single company usually takes responsibility for the design and performance of the entire upgrade facility. Such a "turn-key" arrangement protects the system owner from potential disputes over the failure of one system component.

The following technologies are commercially available to remove the remaining three of the four major CMM contaminants:

Oxygen Removal: After nitrogen rejection, deoxygenation is the most technically challenging and expensive process. It is especially important since most pipelines have very strict oxygen limits (typically 0.1 percent or 1,000 parts per million). NRU technologies such as PSA will experience oxygen rejection in proportion to nitrogen rejection and may need very little deoxygenation as a final processing step. Oxygen rejection associated with cryogenic or solvent absorption NRUs is more critical due to explosion danger, and it must be the first system component. Since deoxygenation results in a substantial temperature rise, if inlet gas is likely to contain over 1.5 percent oxygen, a two-stage recycle system is needed to avoid unacceptably high temperatures.

Carbon Dioxide Removal: Several technologies are available commercially, including amine units, membrane technology, and selective adsorption. Amine units are tolerant of only low levels of oxygen in the feed stream, so the amine unit must be downstream of the deoxygenation unit.

Water Vapor Removal: Dehydration of CMM is the simplest part of any integrated system design. Inadequate water removal, however, can result in corrosion damage to delivery pipes and can be quite serious. Most system suppliers will employ a molecular sieve dehydration stage because of its proven record and economical operation.

4. Commercial Applications

The first CMM upgrade facility in the U.S. was installed by BCCK Engineering, Inc. in 1997 in Southwestern Pennsylvania. Since then, 13 additional commercial-scale CMM upgrade facilities have come on line at active and abandoned mines, and three additional facilities are awaiting start up. Figure 2 shows the locations of these projects, while Table 2 lists these facilities, including their location, type of feed gas, and throughput capacity.

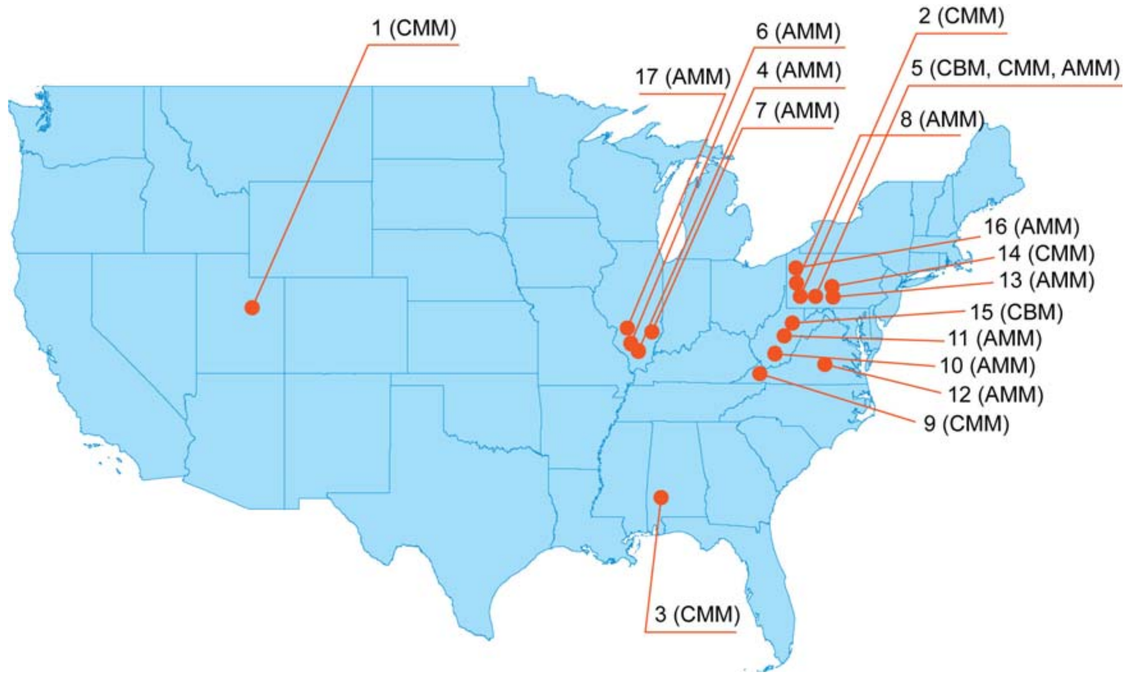

Figure 2. Locations of Operating CMM Upgrade Facilities

Table 2. Operating CMM Upgrade Facilities

Vendor	Location	Feed Gas	Inlet Capacity (Mmscfd)	Inlet N_2 Concentration
AET (Vendor profile on pg. 11)	Price, Utah	CMM	8	~15%
BCCK (Vendor profile on pg. 12)	Waynesburg, PA	CMM	12	10–25%
BCCK	Brookwood, AL	CMM	12	28–32%
BCCK	Marion, IL	AMM	12	15–30%
D'Amico Technologies (Vendor profile on pg. 13)	Northern Appalachia	CBM*, CMM, AMM	5	2-3%
Guild (Molecular Gate)** (Vendor profile on pg. 14)	Illinois Basin	AMM	1.0	$\leq$10% (plus 1% CO_2)
Guild (Molecular Gate)	Raleigh, Illinois Basin	AMM	2.5	$\leq$15% (plus 3% CO_2)
Guild (Molecular Gate)	Southwestern PA	AMM	2.0	13% (plus 2% CO_2)
Guild (Molecular Gate)	Virginia	CMM	1.5	17% (plus 3% CO_2)
Guild (Molecular Gate)	West Virginia	AMM	0.8	6% (plus 1% CO_2)
Guild (Molecular Gate)	West Virginia	AMM	1.5	30% (plus 3% CO_2)
Guild (Molecular Gate)	Virginia	CMM	10	17% (plus 3% CO_2)
Guild (Molecular Gate)	Pennsylvania^	AMM	1.5	40% (plus 1% CO_2)
Guild (Molecular Gate)	Pennsylvania	CMM	1.5	15% (plus 5% CO_2)
Guild (Molecular Gate)	West Virginia^	CBM	1.0	8% CO_2 only
Guild (Molecular Gate)	Pennsylvania^	AMM	2.0	40% (plus 1% CO_2)
Guild (Molecular Gate)	Illinois	AMM	0.5	< 10% (plus 1% CO_2)

* Coalbed methane

**The Guild / Molecular Gate™ technology is licensed to Guild from Engelhard (now BASF).

^ Awaiting start-up

The following examples demonstrate how some CMM drainage projects have successfully combined various gas upgrading technology options to purify lower-quality CMM to pipeline quality specifications.

Example #1

The D'Amico Technologies project underway in northern Appalachia performs limited CMM processing for sale to a natural gas pipeline. The developer avoids the costly NRU step by employing three techniques to maintain acceptable product specifications:

- *Feed gas control* – accepting only the high-grade or lightly contaminated CMM, especially with respect to nitrogen.
- *Carbon dioxide and water vapor removal* – using a proprietary technique to reject carbon dioxide.
- *Blending* – using a supply of very high-grade CMM, the project employs controlled blending to bring into compliance a substantial flow of slightly off-specification product.

Example #2

In 2000, Jim Walter Resources (JWR) began operating a BCCK gas processing plant at their Brookwood, Alabama mine to supplement their high-quality methane production by upgrading low-quality gas. The fully integrated plant removes water, CO_2, nitrogen, and oxygen. Early in the plant's operation, the low-quality gas was determined to contain sulfur, a not so common CMM contaminant. Although the gas contained only a few ppm of sulfur, it nevertheless caused problems over time for the amine tower (the CO_2 removal component); JWR had to add a sulfur removal component to the overall plant. The plant has continued to operate since startup and currently processes an estimated 8 to 9 Mmscfd of raw gas, producing about 4 Mmscfd of treated gas. During the first five years of operation, the plant was managed on site by BCCK staff under contract to JWR. Subsequently it has been operated directly by the JWR staff.

Example #3

In southern Illinois, Grayson Hill Energy, LLC is employing the Molecular Gate® technology to remove water, nitrogen, and carbon dioxide from abandoned mine methane and low-quality natural gas to produce pipeline quality gas. The plant, which is powered by an onsite tail-gas-fueled generator, removes nitrogen and carbon dioxide in a single step. Gas flow rates to the plant are of the order of 2.5 Mmscfd.

5. Summary of Gas Upgrading Technologies

Five system vendors are currently supplying CMM upgrading technologies to the natural gas market: AET, BCCK, D'Amico Technologies, Guild Associates, and MTR. Another, Northwest Fuel Development, has operated a nitrogen removal system with 1 Mmscfd capacity at two mines in Ohio.

Table 3 summarizes the system providers that have the technical capability to design and provide gas upgrading systems and that have targeted their systems to the CMM market. The Appendix contains a more detailed profile of each of these vendors.

Table 3. Current and Upcoming CMM Upgrade Technology Vendors

Vendor	NRU Technology	Size Range (inlet Mmscfd)	Contaminants Removed	Turnkey?	Status	Comments
Advanced Extraction Technology (Vendor profile: pg. 11)	Solvent Absorption	2 and over	N_2, H_2O	Y	Full-scale operation at coal mine	Engineering for N_2 & H_2O only. Has designated HNNG Development to be their representative in North America.
BCCK (Vendor profile: pg. 12)	Cryogenic	5 and over	N_2, O_2	Y	Full-scale operation at coal mine	Cost competitive at larger scale (e.g., >5 Mmscfd). Provide a fully integrated plant incorporating third-party CO_2 and H_2O removal technologies.
D'Amico Corporation (Vendor profile: pg. 13)	PSA	1 and over	O_2, H_2O	Y	Demonstrated in natural gas fields and commercially available	In addition, the company has implemented a gas upgrade project using an advanced gas production and management approach, avoiding the need for nitrogen rejection.
Engelhard (Guild) (Vendor profile: pg. 14)	Molecular Gate	1 and over	N_2, O_2 (partial), CO_2, H_2O	Y	Full-scale operation at coal mine	May need to add a supplemental deoxygenation system depending on pipeline quality requirements and source gas concentrations.
Engineered Gas Systems Worldwide (Vendor profile: pg. 16)	Cryogenic and membrane	1 and over	N_2, CO_2, H_2O	Y	CMM field demonstration needed	Can design integrated, turnkey systems.
Gas Separation Technology (Vendor profile: pg. 17)	PSA with Zeolites	1 and over	N_2, O_2, CO_2, H_2O	N	Bench-scale testing phase	System will need supplemental deoxygenation system. Has not moved past the bench-scale stage; still seeking development capital.
Membrane Technology and Research (with ABB) (Vendor profile: pg. 18)	Membrane	1 and over	N_2, CO_2,	Y	Full-scale operation at natural gas fields	Continuous process yields steady product stream. Systems can be designed to meet various gas contamination levels and product requirements.
Northwest Fuel Development (Vendor profile: pg. 19)	PSA	1 and over	N_2	N	Pilot NRU has been demonstrated under field conditions	Lower methane yield. Can be competitive with molecular sieve at low N_2 concentrations.
Velocys (Vendor profile: pg. 20)	Microchannel thermal swing absorption	1 and over	N_2	N	Under development	Third-party components needed for CO_2, H_2O, and O_2 removal.

Appendix: NRU Vendor Profiles

Following are vendor profiles for nitrogen rejection technologies that have targeted CMM applications. Integrated upgrading systems that a vendor can offer are also profiled. These profiles were developed based on publicly available information as well as that provided directly by vendor representatives. In some cases (e.g., technologies that have only been demonstrated at bench scale), vendor claims with respect to "proven performance" may not hold true under actual mine conditions. Deviation from proven performance may occur for a number of reasons, including the following:

- Presence of contaminants in CMM that are not usually found in low-grade natural gas
- Variation of CMM flows as wells are disconnected and reconnected
- Variation of CMM contaminant levels over time and location
- Integration of system components that may not be fully compatible (e.g., supplied by a subcontractor)

A.1 Advanced Extraction Technologies, Inc. (AET)

Nitrogen rejection: Solvent Absorption

Other contaminants removed: H_2O

Third party equipment needed to remove: CO_2, O_2

Flow rate limitations: None

Feed quality limitations: None

Status: Commercially available

Contact: Name: Tom Gaskin, VP Technology
Address: 2 Northpoint Drive, Suite 820
Houston, TX 77060-3237 USA
Tel: (281) 447-0571
Fax: (281) 447-5601
E-mail: tomg@aet.com
Website: http://www.aet.com

Commercial history: AET offers full-scale 5 Mmscfd and 15 Mmscfd plants for rejection of nitrogen, with feed gas nitrogen content of about 15 percent. AET's first CMM application began operation at the Aberdeen Mine near Price, Utah in June 2007.

Description of system(s) and performance: AET's process requires oxygen and carbon dioxide removal prior to removing nitrogen and water.

Following O_2 and CO_2 removal, the partially processed feed gas is chilled with propane refrigeration and ethylene glycol injection. Ethylene glycol and water separate, water exits, and ethylene glycol is regenerated, while the cold feed gas is brought into contact with an appropriate chilled solvent in an absorption tower. Nitrogen exits the absorber as the "overhead" product. Methane is absorbed, and the rich solvent is the "bottoms" product of the absorber. Flash separation removes the absorbed methane and heavier hydrocarbons from the solvent by reducing the pressure of the absorber bottoms stream in multiple steps to minimize gas compression. Methane released during flash separation is compressed to sales pressure. After methane release, the lean solvent is pumped to higher pressure, chilled, and returned to the absorber.

AET notes that its technology exhibits infinite CO_2 tolerance without freezing and flexibility in terms of its response to feed rate and compositional changes.

Services offered: AET licenses the use of its NRU and water removal technology and provides process engineering support. HNNG Development (Glen Rector; (713) 225-6801; www.hnngdevelopment.com) is the sole representative for licensing the process in North America.

A.2 BCCK Engineering, Inc.

Nitrogen rejection: Cryogenic

Other contaminants removed: O_2

Third party equipment needed to remove: CO_2, H_2O

Flow rate limitations: The BCCK process is most cost effective at raw gas inflow rates higher than 5 Mmscfd.

Feed quality limitations: None

Status: Commercially available

Contact:

Name:	Gregory L. Hall, P.E., Sales Manager or R. Clark Butts, P.E., President
Address:	2500 North Big Spring Street, Suite 230 Midland, TX 79705
Tel:	(432) 685-6095
Fax:	(432) 685-7021
E-mail:	Greg Hall: greghall@bcck.com
Website:	www.bcck.com

Commercial history: BCCK Engineering has installed three full-scale CMM upgrade facilities to date. The first was installed in Pennsylvania in 1997. All three facilities upgrade methane to meet natural gas pipeline requirements.

Description of system(s) and performance: BCCK's CMM upgrading plants are completely integrated facilities, including a proprietary oxygen extraction process (catalytic oxidation) and BCCK's patented Nitech™ nitrogen extraction process. The system integrates conventional CO_2 removal (amine process) and dehydration equipment supplied by other vendors. BCCK's plants operate over a wide range of inlet conditions while meeting sales gas specifications.

BCCK specializes in nitrogen extraction using cryogenic technology. The Nitech™ process is capable of providing over 99 percent hydrocarbon recovery. Nitrogen vented from the NRU contains only a small amount of methane and no volatile organic compounds. This efficiency eliminates the need to flare residue product from the facility. The company's catalytic oxygen extraction process can meet stringent oxygen specifications (e.g., up to 10 ppm) in the sales gas. BCCK has integrated the oxygen extraction process with other plant components in order to utilize the heat produced, thus reducing fuel gas demand.

Services offered: BCCK's services include designing, procuring, and installing all plant equipment; start-up; and operation (if requested).

A.3 D'Amico Technologies

Nitrogen rejection: PSA

Other contaminants removed: None

Third party equipment needed to remove: CO_2, H_2O, O_2

Flow rate limitations: None

Feed quality limitations: The D'Amico Technologies' currently active CMM drainage and treatment project uses advanced techniques for gas capture and handling that minimize the level of contamination in the gas fed to the upgrade plant, avoiding the need for nitrogen rejection (the costliest step in CMM processing). The company also employs high-quality gas for blending to increase the energy content of the product stream.

Status: Commercially available, but currently not employed at a coal mine

Contact:	Name:	Joseph D'Amico, President
	Address:	6422 Oak Park Court Linthicum, MD 21090
	Tel:	(410) 859-3044
	Fax:	(410) 859-3044
	E-mail:	damico.corp@verizon.net
	Website:	N/A

Commercial history: D'Amico Technologies' patented nitrogen rejection technology has been tested in natural gas fields in Texas, Colorado and Kansas, and is commercially available though not as yet put into operation at a coal mine. The company has successfully developed and implemented a gas upgrading and pipeline injection project that avoids the need for nitrogen rejection; the facility, located in the Northern Appalachian coal basin, is currently active.

Description of system(s) and performance: D'Amico Technologies employs a patented PSA nitrogen rejection process that includes a carbon molecular sieve in the bed. It preferentially adsorbs the hydrocarbon and lets the contaminants (nitrogen, some oxygen, and water) pass. Third-party components can be added for removal of other contaminants. There are no data on performance of this technology at an actual mine, since it has yet to be implemented for CMM processing. The gas management approach being employed at D'Amico's current project includes use of small, satellite gas-processing plants at the wellheads upstream of the larger centralized processing facility.

Services offered: D'Amico Technologies can design and implement fully integrated gas processing systems using advanced technologies. In addition, the company is able to provide gas drainage expertise to produce gas with as little contamination as possible, thereby reducing the gas-processing requirement and maximizing project profitability. Their approach to gas management enables handling daily changes in gas supply. The company also offers consultation services and assistance in securing pipeline interconnection, gas sales, and carbon offset agreements.

A.4 Guild Associates, Inc.

(Exclusive U.S. licensee of Engelhard's Molecular Gate technology)

Nitrogen rejection: Molecular gate

Other contaminants removed: CO_2, H_2O, O_2 (partial – see text below), H_2S (if necessary)

Third party equipment needed to remove: O_2, when required to be removed to low levels

Flow rate limitations: None

Feed quality limitations: None

Status: Commercially available

Contact:
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Dublin, OH 43016
Tel: (908) 752-6420
Fax: (614) 798-1972
E-mail: Mike@moleculargate.com
Website: www.moleculargate.com

Commercial history: Twelve full-scale plants are in or are nearing operation (25 in total on natural gas): one processing virgin coalbed methane for CO_2 removal, three processing CMM, and eight processing methane from abandoned mines.

Description of system(s) and performance: The technology consists of specialty adsorbents and advanced PSA processes that are jointly offered as fabricated equipment by Guild Associates, Inc. and is based on the Molecular Gate technology licensed by Guild from Engelhard (now BASF) Corporation. The Molecular Gate process will remove all the water and CO_2 and a portion of the N_2 and O_2 in a single step. If required, the process can also remove H_2S. In most cases, the nitrogen specification is 4 percent and typically the methane recovery rate is 92 percent.

The Molecular Gate system (explained in section 3) for upgrading nitrogen-contaminated CMM uses molecular sieves with pore size of 3.7 angstroms, nitrogen and methane molecular diameters being approximately 3.6 angstroms and 3.8 angstroms, respectively. This adsorbent permits nitrogen and the much smaller CO_2 (3.3 angstroms) and O_2 (3.5 angstroms) molecules to enter the pore and be adsorbed while excluding the methane, which passes through the fixed bed of adsorbent at essentially the same pressure as the feed. One major advantage of the process is that the CO_2 is completely removed in a single step being much smaller in size, while the nitrogen and oxygen are removed to pipeline specifications. Water is also a small molecule and adsorbs strongly; typically, the system is designed to remove water so the feed is pre-dehydrated to moderate levels.

The Molecular Gate system can operate over a feed pressure range from as low as 50 psig to 600 psig or more, which suits CMM feed pressure which is typically in the range of 100 psig. This fits the conditions for an oil-flooded screw compressor with atmospheric pressure suction and discharge as required in a single stage. A pressure of about 100 psig offers an optimal balance between the needs of the compressor and the Molecular Gate unit because it provides product at 90 psig, which allows the product compressor to be a two-stage reciprocating machine. Since the product at the suction point is dry and CO_2-free, there are no corrosion issues; this advantage voids the need for special materials and extends the life of the compressor.

Although the Molecular Gate process will remove O_2 at about the same or slightly lower rate as N_2, O_2 removal is recommended ahead of the Molecular Gate, since accumulating concentrations of O_2 in the low-pressure tail gas pose a risk of explosion. As the rejected O_2 concentration approaches about 10 percent (the lower explosive limit of O_2 in methane) in the tail gas, a safety issue can develop since the tail gas continue to contain small amounts of methane.

Guild states that it removes the N_2 from the methane, leaving methane at high pressure, while all other processes remove the methane from the N_2, producing methane at low pressure—a significant economic advantage over other technologies.

Services offered: Guild Associates will design, build, and start up an integrated CMM upgrade plant, including providing compression and peripheral equipment, and will train the operators.

A.5 Engineered Gas Systems Worldwide (EGSWW)

Nitrogen rejection: Cryogenic

Other contaminants removed: CO_2, H_2O, O_2

Third party equipment needed to remove: N/A

Flow rate limitations: None

Feed quality limitations: None, although their process is more cost effective at higher inlet flows and methane concentrations

Status: Field demonstration needed

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Commercial history: EGSWW has targeted biogas and landfill gas upgrading (among other applications) in their technology portfolio and could engineer an integrated system for upgrading coal mine methane. As of this report, however, they have not demonstrated their process in the field.

Description of system(s) and performance: The proprietary EGSWW process involves an initial dewatering step followed by a cryogenic stage for nitrogen removal and a hollow-fiber membrane stage for CO_2 removal.

Services offered: EGSWW can provide fully integrated, turnkey CMM upgrade systems for domestic applications. They can custom design systems that are tailored to meet the specific gas processing needs of a given project.

A.6 Gas Separation Technologies, LLC (GST)

Nitrogen rejection: PSA with natural zeolites

Other contaminants removed: CO_2, O_2 (partial – see text below)

Third party equipment needed to remove: H_2O, O_2

Flow rate limitations: The process is designed to be economical for relatively small gas flows from 0.5 to several million cubic feet per day.

Feed quality limitations: Less than 40 percent nitrogen

Status: Research and development; field demonstration needed

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Commercial history: The technology has not yet been proven beyond bench-scale testing, and the process for removing oxygen and nitrogen is not yet perfected. The low oxygen specification for pipeline gas (0.1 percent) might be the most difficult to meet. As of this writing, the developer was still seeking sources of development capital to move the technology past the bench-scale stage.

Description of system(s) and performance: Gas Separation Technologies uses two distinct pressure swing adsorption systems: the patented Carbo-X™ process for carbon dioxide removal and Air-X™ for air/nitrogen removal. Both systems employ a natural zeolite adsorbent. Inlet gas is pressurized and dehydrated, after which it travels to the Carbo-X™ unit which reduces CO_2 to about 0.5 percent. Upgraded gas then travels to the Air-X system. A supplemental deoxygenation step will probably be necessary for most CMM applications. The Carbo-X™ component uses an air rinse instead of pressure reduction for regeneration, and can achieve a high level of separation at low operating pressures—a feature that reduces both operating and capital costs. Increasing operating pressures will improve the purity even further.

Services offered: Once GST has perfected both system designs, it will offer a full-scale facility. It will probably have to work through a turnkey constructor that has sufficient financial strength to stand behind system guarantees.

A.7 Membrane Technology and Research, Inc. (MTR)

Nitrogen rejection: Membrane

Other contaminants removed: CO_2, with a separate membrane

Third party equipment needed to remove: H_2O, O_2

Flow rate limitations: The process is most cost effective at flows ranging from 1-20 Mmscfd.

Feed quality limitations: None

Status: Commercially available

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Commercial history: MTR's membrane systems have been field-proven in natural gas processing applications such as nitrogen removal and fuel gas processing.

Description of system(s) and performance: The MTR NitroSep™ process uses a selective membrane that allows hydrocarbons to pass through but retains nitrogen. Typically their process creates two treated streams: a low-nitrogen (<4 percent N_2) product stream that is enhanced in hydrocarbons, and a high-nitrogen (30-50 percent N_2) side stream that will contain some methane and can be used as a fuel for compressors powering the membrane separation process. In some applications, a third concentrated-nitrogen (60-85 percent N_2) waste stream is also generated.

Treatment of gas streams with low levels of nitrogen contamination may require only a single membrane to achieve product gas specifications. Two or more membranes may be required for more concentrated streams. The company can engineer its treatment systems specifically to meet requisite product gas specifications depending on the quality of the feed gas stream.

The MTR process is continuous (not batch mode) and is able to produce a steady product flow with 80-90 percent methane recovery.

Services offered: MTR can provide a system combining one membrane for nitrogen removal and another for CO_2 removal. Third party processes for water removal and oxygen removal must be added, either upstream or downstream of the MTR membrane(s), to create a fully integrated CMM upgrade system.

A.8 Northwest Fuel Development, Inc. (NW Fuel)

Nitrogen rejection: Continuous PSA

Other contaminants removed: None

Third party equipment needed to remove: CO_2, H_2O, O_2

Flow rate limitations: None

Feed quality limitations: Yes – feed should contain $\geq$90 percent methane

Status: Demonstrated under field conditions

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Commercial history: The NW Fuel Continuous Pressure Swing Adsorption (CPSA) process has been demonstrated at full scale (1 Mmscfd unit) at two coal mines for a limited term.

Description of system(s) and performance: The CPSA process is a simple, high-throughput process capable of separating methane from nitrogen in lightly contaminated CMM gas streams. Given its simplicity, the process can be applied economically to small sources of CMM. A unit capable of processing 1 Mmscfd of CMM is about the size of a pickup truck.

The NW Fuel system uses a methane-selective absorbent. A disadvantage of the NW Fuel system is that it does not have high product recovery efficiency. About 30 percent of the methane in the feed stream goes into the byproduct stream that is available for onsite power generation or other applications.

Services offered: NW Fuel can provide an integrated CPSA system by adding the appropriate carbon dioxide, oxygen, and water vapor removal systems from third party suppliers. The company has installed and operated such systems, although its experience with oxygen removal systems is limited.

A.9 Velocys, Inc.

Nitrogen rejection: Thermal swing absorption

Other contaminants removed: None

Third party equipment needed to remove: CO_2, H_2O, O_2

Flow rate limitations: Velocys is targeting small flow-rate CMM applications rather than trying to compete with cryogenic systems which are economical for large flow-rate applications.

Feed quality limitations: None for CMM applications

Status: Under development

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Commercial history: Velocys Inc. is pursuing a breakthrough in nitrogen rejection gas processing efficiency through the application of their microchannel chemical processing technology. By combining that technique with selected adsorbents, Velocys is striving to achieve ultra-fast thermal swing adsorption. Bench-scale testing has been conducted using microporous carbon as the adsorbent and employing a thermal swing time of 10 seconds and a bed differential temperature of 20°C. In testing, a feed gas stream of 70 percent methane and 30 percent nitrogen was separated into a product stream of 92 percent methane and 8 percent nitrogen. Further testing and development is underway.

Description of system(s) and performance: The Velocys microchannel technology is based on the principal that increased surface area results in increased chemical reaction rates. Their goal is to dramatically increase the rate at which temperature swings can occur and to direct a greater amount of heat where it is needed to increase the nitrogen removal rate.

Services offered: The Velocys system at present is solely targeting nitrogen removal. Third party components would need to be secured for carbon dioxide, water, and oxygen removal for a fully integrated gas processing plant.